6-1-2010

Modeling and optimization of supply chain cost of responsiveness

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By

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B.Sc. in Mechanical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Engineering

With specialization in

Industrial Engineering

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Under the supervision of

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Spring 2010

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Dedication

To my father…

Si vales, valeo

Acknowledgement

I find myself impelled to thank Dr. Abdelghani Elimam, my supervisor, for his altruistic support in bringing this work to light. Without his firm pursuit of research excellence; I wouldn't have learned that much. At the end you are my best mentor.

Dr. Lamyaa El Gabry gave me tremendous support during the past three years when I worked with her as a TA. I can't write this section without thanking her from the bottom of my heart. Dr. Laymaa is the first, and best, professional manager I worked with.

My Officemate, Mokhtar Kamel, sometimes a person may go astray in his pursuit but with your companionship I made it to the end of the road (and so did you). You are the best officemate I ever had.

Mohamed Okasha's help as a lab engineer made it possible for me to finish my thesis computational work where I worked in his lab late at night. His assistance and flexibility are invaluable to me.

Abstract

The American University in Cairo

Modeling and Optimization of Supply Chain Responsiveness

By: Moataz Mohamed Magdy Hamouda Ahmed

Supervised by: Dr. Abdelghani Elimam

In today's ever increasing competitive business world, a responsive Supply Chain (SC) should adapt itself quickly to customer demands resulting into maximum benefits to all its primary stakeholders. The objective of this work is to provide a managerial tool that optimizes the cost of responsiveness of supply chains where various transportation durations are present between the SC components, and to determine the weakest links in the SC that need strengthening for elevating the overall responsiveness. For these objectives a mathematical model was formulated and solved using CPLEX. Assessing supply chain's responsiveness is discussed in this work as well using the cost of responsiveness, SC output rate and production slack times. The computational results show that the mathematical model is effective in planning and synchronizing production, shipping and storage in a supply chain from start to end so that the cost of responsiveness is minimized while customer demands are fulfilled under limited outsourcing.

List of Figures

List of Tables

Table of Contents

List of Acronyms and Abbreviations

APICS	American Production and Inventory Control Society
ATO	Assemble-to-Order
BOM	Bill of Materials
BTO	Built-to-Order
CCR	Capacity Constrained Resource
CR	Cost of Responsiveness
DC	Distribution Centers
FP	Finished Product
GDC	Global Distribution Centers
JIT	Just in Time
LDC	Local Distribution Centers
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MTF	Make-to-Forecast
MTO	Make-to-Order
MTS	Make-to-Stock
NUMMI	New United Motor Manufacturing, Inc.
OR	Supply Chain Output Rate
RM	Raw Material
SC	Supply Chain
SCM	Supply Chain Management
ST	Slack Time

Chapter 1

Introduction

1.1 Historical Background

During the 70's and 80's of the last century, Japanese companies outperformed their Western counterparts in the quality of their products, efficiency and responsiveness to customer demands (Lubben 1988). After the Japanese impressive performance in the manufacturing arena the rest of the world became inquisitive about their success formula which was believed to be "inventory control" (Shonberger 1982).

The genesis of the Japanese efficiency lies in the fact that Japan is a small overpopulated island with handicapping limited resources (Shonberger 1982). This raised the awareness of the Japanese causing them to regard idle inventory as a waste of scarce material, and indirectly energy, and their storage as a waste of the scarce space.

1.2 Supply Chain Responsiveness and Competitiveness

A supply chain is defined to be "a sequence of organizations that are involved in producing and delivering a product or a service" (Stevenson 2007). It is not in a company's benefit to buffer itself with a needless pile of inventory as a result of its lack of confidence and uncertainty in its suppliers or (considering the other side of the coin) its customers. Hence, the term Supply Chain Management (SCM) was defined to be "the strategic coordination of the supply chain for the purpose of integrating supply and demand management" (Stevenson 2007) where the American Production and Control Society (APICS) defines the term to be "design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally."[1]

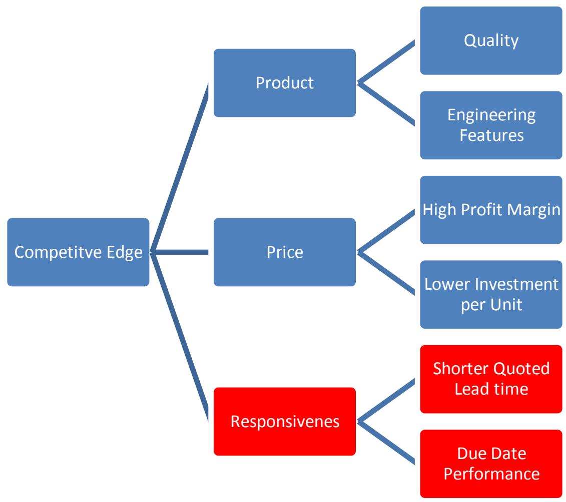

Figure 1: Competitive Edge Tree (Goldratt and Fox 1986)

Company's responsiveness, one of the competitive edge elements depicted in Figure 1, is seen to have two primary components:

1. Short lead times
2. Due date performance

The lead time was, logically, found to be enhanced significantly by lot splitting and overlapping. Lot splitting (or small transfer batch policy) takes advantage of keeping all the resources busy most of the time resulting into a significant decrease in the overall lead time. Responsiveness is directly related to due date performance, defined as the ability of consistently meeting the due date promised; hence increasing the SC's due date performance via shortening lead time and maintaining it gives the SC a competitive edge (Goldratt and Fox 1986).

[1] www.apics.org

Without being responsive to customer demands, a SC whether it is a military, a series of companies or organizations, jeopardizes its throughput. To put it the way a manager in Adidas states it: “That is the problem. If Adidas takes too much time to spot and respond to changing consumer preferences -not to mention manufacture the products- it may miss sales opportunities and/or find itself stuck with footwear nobody wants” (Productivity Press 2006).

1.3 Responsiveness, Geography, Logistics and Drawbacks of being too Lean

Since suppliers in Japan can ship daily to their customers; geography played an important role in facilitating the Japanese supremacy in operational management. In fact the West considered geography to be a barrier that restrained it from following up with the Japanese (Shonberger 1982). Geography has always played an important role in manufacturing and industry in general. However, as SCs became global as a result of outsourcing from other countries in the globe making advantage of cheap labor or the import of necessary unavailable raw materials; the question of logistics and transportation of goods became of extreme acuity. The JIT philosophy deliberately worked with the minimum inventory possible, but this is a very risky approach that might ruin companies and even countries (Stevenson 2007). The New United Motor Manufacturing, Inc. (NUMMI), the joint venture agreement between GM and Toyota mentioned earlier, suffered from an abrupt unforeseeable strike by the dock of Oakland workers causing them to halt production in the entire facility. Additionally transportation costs can increase significantly with the increase in the number of consignments resulting into an increase in the entire SC operating expenses. Since responsiveness has two components: high performance due dates and shorter quoted lead times; the two extremes that bound the entire SC responsiveness are the very expensive and slow *Just-in-Case strategy* and the agile (yet riskier) *Just-in-Time strategy*.

1.4 The Premise for SC Responsiveness

In the 1980's Japan's case, geography facilitated transportation among SC components resulting into reduction of the lead time and the unnecessity of large amounts of safety stocks and as a natural consequence of this configuration small batch sizes caused the lead time to shorten further and the operational expenses to decrease. Today a geograhpically disadvantaged SC can choose among fast transportation modes to come as close as possible to the Japanese model.

The overall lead time of the SC is affected by the durations which transportation modes can offer. By controlling the lead time through the choice of modes, level of safety stocks and batch sizes, SCs can respond economically to customer demands with limited outsourcing from other SCs.

Problem Definition

All SCs need to be responsive to its customers and in pursuing that goal SCM may seek various alternatives like reducing production time via lot splitting or decreasing setup time, investing in either finished products or raw materials safety stocks to buffer disruptions coming from the downstream or upstream respectively, opening retail outlets near the customer's market, shipping via faster transportation modes. More than that, to be responsive companies may resort to higher reliability suppliers; hence by increasing the reliability of the SC, the responsiveness is also elevated. Because responsiveness is a critical competitive edge for SCs (Goldratt and Fox 1986, Stevenson 2007), they need to manage how to respond efficiently to customer demands, know the potential weak spots and assess the implementation of new policies on the responsiveness of the SC.

For a given SC configuration, namely SC customer fulfillment strategy, production capacities, available transportation modes, costs associated with all the activities and customer demand (quantity and time) it will be desired to know how to optimally respond, the cost of responsiveness and how does this responsiveness change with customer demand on the SC. It is also beneficial to measure the ability of the SC while responding.

Responsiveness Definition

Before introducing the mathematical model, it is important to discuss the definition of responsiveness, because this is translated into an objective function and constraints in the model itself.

In operational management context, as depicted in Figure 1, Goldratt defines a responsive company as the one having "shorter quoted lead times and high due date performance" (Goldratt and Fox 1986). Goldratt's addition of due date performance as the other component of responsiveness sheds light about the dependability of the production facility. That is the production plant can actually perform the required task consistently.

The definition proposed for SC responsiveness is "The ability to fulfill customer demands by the required due dates with limited outsourcing".

Each company in the supply chain being a production facility, warehouse, retail store …etc is generally called a *component*. The component can either be a child or a parent, and it can be a child and a parent at the same time. A child component supplies its parent by either components or finished products.

The model was tested on two main cases a base case, inspired by an actual supply chain of a car battery manufacturer, and a big case to test the capabilities of the model. In each of the cases the SC's components can be categorized into three main categories:

1. Customers: pure receivers of products. The optimization program terminates after all the customers of the SC receive their requested products by the due dates they have established.

2. Manufacturers: which can be further classified into pure suppliers forming the ultimate upstream of the SC with no children and manufacturers who take their raw material from actual suppliers in the SC and add value to them then send them to their parents.
3. Dealers: components that act as intermediaries between manufacturers and clients. In reality those are final product warehouses from which transportation takes place to either other dealers, or to customers.

Supply Chain Mechanics: pure suppliers provide manufacturers their raw material which they need to process and then these manufacturers can take any of the following roles:

a. Supplier to another manufacturer
b. Supplier to a dealer
c. Supplier to a customer

Objectives

The objectives of this study are to:

1. Optimize the cost of responsiveness to customer demand
2. Assist in targeting improvements to SC links which will leverage the responsiveness performance
3. Numerically assess the responsiveness of SCs

The optimization will take place via the mathematical model formulated taking into account the different transportation modes along each link.

Thesis Overview

The relevant literature is reviewed and presented in chapter 2. Chapter 3 includes the mathematical model development, where the formulation, characterization and the solution approach are presented. The computational work including results and interpretation is given in chapter 4. Finally, the conclusions and future work are stated in chapter 5.

Chapter 2

Literature Review

In the literature review chapter the notion of responsiveness and its ingredients from the perspective of other researchers will be summarized and commented on. After reviewing the literature it was found that responsiveness is mainly affected by the SC configuration, batch sizes, transportation duration, components' relationship and level of cooperation and the degree of utilization of safety stocks. Figure 3 shows the relevant operational responsiveness factors.

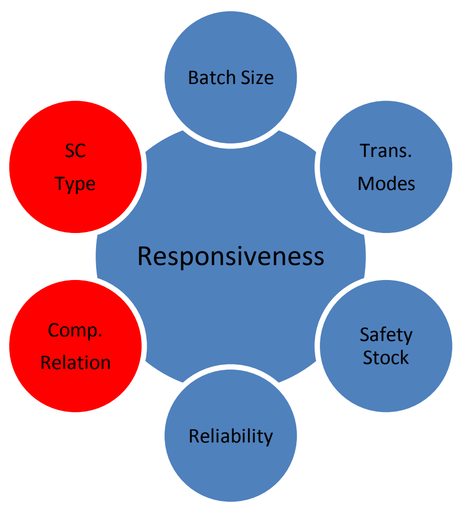

Figure 2: SC Operational Responsiveness Factors

2.1 Lead time

At the heart of responsiveness lies the issue of lead time reduction. Lots of factors influence the lead time of a SC. The configuration of the SC, Make-to-Order (MTO) not to make orders until a firm order is obtained, Make-to-Stock (MTS) to make and store products, Make-to-Forecast (MTF) to base production planning on forecasts of the future, or Assemble-to-Order (ATO) to make common assemblies that are used in most products and MTO other parts, has a significant impact on lead time reduction. Batch sizes and transportation modes/durations impact the lead time and cycle time significantly as well. Hence SC configuration, batch sizes and transportation duration between components are the primary factors that affect the lead time.

As different product types influence facilities' layouts, they also influence the entire SC. Wong et al. (2006) worked to find the determinants upon which the responsiveness of SC should be assessed and the optimum SC configuration to satisfy both the customer and company. The determinants chosen were:

1. Uncertainty
2. Delivery time: lead time from the order point till delivery
3. Contribution margin: incentive to invest in reducing lead time and/or inventory buffers

Wong et al's analysis is primarily qualitative in nature, and it doesn't show which factors are the most important. From their analysis demand nature and lead time of each product will dictate a certain SC configuration however for a company with different categories of products, two SC configurations might not be feasible.

Yimer and Demirli (2009) propose a way to manage a Build-to-Order (BTO) SC via the means of a Genetic Algorithm (GA). BTO is a SC that has the benefits of both the lean MTO and the agile MTS SCs as it is considered to be a hybrid SC between MTO and MTS. The customary components that go inside the final product are manufactured via the MTS configuration to maintain a certain service level, while the demand of the final customers (retailers) are made only after their orders are issued. Hence, there is under-the-skin standardization that can be utilized by the SCM. This concept is manifested in making some of the standard assemblies ready to be used at the main assemblers' warehouses as they are going to be needed anyway.

The figure of the SC that the authors provided in their article, describes the type of the SC that can be managed using their model. Basically, the SC is composed of four tiers. Namely (from downstream to upstream) the components are: retailers (customers), distributors, assemblers (manufacturers) and fabricators (RM providers). The two configurations of SCs (MTS) and (MTO) are decoupled at the assemblers tier. The authors give an example that follows this configuration with the furniture industry. This model or configuration is in congruence with lots of published work in the literature. However, some models (like SCOR) consider the supplier's suppliers and customer's customers in the supply chain thereby expanding it to include a larger terrain.

A Mixed Integer Linear Programming (MILP) model was formulated by the authors to solve this type of configuration SC problem. The others opted to solve the problem in two phases. The first phase deals with the distribution and production and the other phase is concerned by the component fabrication and raw material procurement. The first phase determines the optimum lot sizes, inventories, backorder quantities and transfer batches that will result into the lowest SC production and distribution costs. The optimum amount of quantities that the assemblers have to use are going to be fed into the second phase model in the form of constraints to determine the optimum decision variables that will result into satisfying them while keeping the costs at minimal. The authors didn't take into consideration the effect of various transportation modes. They didn't formulate the model to solve problems dealing with SC composed of assemblers feeding other assemblers. Based on their conclusion, the GA which they formulated resulted into better results (not less than 99% of the optimum value obtained by, the programming language, LINGO) for different scenarios. The authors work is only applicable for SC with four tiers and it doesn’t show the effect of various transportation modes on the responsiveness of the SC.

Ouhimmou et al. (2008) formulated a mathematical model to regulate the Supply Chain Operations Planning (SCOP) aspect of a furniture SC in Canada. In their case the SC was composed of four tiers (upstream to downstream): public forests, sawmills, kilns and furniture mills. The four tiers assumption was also the underlying assumption of Yimer and Demirli (2009) as well who proposed that furniture SCs can fit into this configuration nicely. The difference between the two works is that unlike Yimer and Demirli (2009), the authors solved the mathematical model of the furniture SC in one phase right away. Attempting to solve the model without dividing it resulted into huge consumption of time on the optimization code CPLEX (for large numbers of binary variables the software wasn't even capable to converge to a feasible solution), which motivated the authors to make a heuristic to solve the model within a reasonable time for the industrial case study which was actually composed of 40 logs suppliers, 2 sawmills and 16 kilns with 2,000,000 continuous variables, 8,000 binary variables and 3,000,000 constraints. Hence, the model was an MILP especially tailored for the furniture industry and was not generic that deals with any four tiers BTO SC, and again the effect of transportation modes was not included probably because it has less significance in this particular furniture SC.

Under the assumption that planned lead times are essential ingredients in SCOP, Spitter, et al. (2005) formulated a Linear Programming (LP) model that determines the amounts to be processed via the different SC components (resources), inventory and backordered quantities that will minimize the incurred operational costs on the SC. In their analysis the authors assumed that the due dates have a reliability of 100%. An arbitrary SC was designed to test the applicability of the models presented by the authors in which they tested the effect of changing the number of components, products and demand on the optimum solution and computational time. The authors used CPLEX and didn't need to resort to heuristics as the model was purely linear with no integers, or binaries (which usually result into combinatorial exchanges and lengthening of the computational time), hence they concluded that the dual-simplex is the best algorithm for solving the SCOP model at hand. Because the model didn’t include binary variables, hence the level of possible combinations was very low indicating that the model is purely theoretical and can’t be used in SCs with various alternatives on hand.

JIT philosophy can be adopted in a mathematical model and used for the distribution phase in a SC (Wang et al 2004). The authors presented the case of a SC that needs to fulfill customer demands in a JIT manner. In their analysis the authors represents the pull system via discrete ordered quantities in the planning horizon that need to be met through a limited capacity warehousing system. Since the fulfillment is done in batches, to be effective the SC model should minimize earliness as well as tardiness. However, the main advantage of the model they formulated is that it is purely an LP model which can be solved efficiently and optimally using the regular operations research algorithms. The authors succeeded in transforming the objective function, which is not continuously differentiable, into a linear continuous one by substituting chunks of variables in the objective function with ones that cannot maintain positive values at the same time in a way similar to the unrestricted variables notion in the traditional OR techniques. Like Spitter, et al. (2005) the formulated model contains no binary variables indicating the nonexistence of choosing among descrete alternatives which may happen in reality.

The level of planning detail in SC can be expanded to include the shop floor production level of individual facilities such that the total inventory and operating costs of the entire SC is reduced (Sawik 2009). The model considers three tiers BTO SC with raw material suppliers as the upstream edge, followed by assemblers and finally the customers. The mathematical model attempts to decrease inventory in the system while fulfilling customer demands. The mathematical model is an MILP model, and it goes a step further than regulating the material flow among the SC components as it schedules the production plans inside the production facilities as well. The model optimally decides the allocation of parts to production lines within each facility. However, it doesn’t take into consideration the various transportation modes and their impact on the lead time of the SC.

2.2 Lead Time Performance, Dependability, Reliability and Availability

While shorter quoted lead time surely affects the responsiveness of the SC; consistency of performing with that lead time is another dimension of responsiveness that needs to be coupled with the reduced lead time. Goldratt and Fox (1986) noted that relationship and depecited it in (figure 1), however their definition for that second primary component lacks robustness as they called it “due date performance”. In the literature the “performance” was found to be named differently as reliability, avialability or service level. The notion of SC reliability and availability will be discussed in this section, whereas service level is discussed in the safety stock utilization section in the literature.

The reliability of a SC composed of global dealers, local dealers and customers can be calculated after determining their locations, customer demands and replenishment speed (Wang, Lu and Kvam 2006). The authors considered the customer fulfillment strategy, Distribution Centers (DC) capacities and the physical distance between the customer and DC to be of major importance in determining the overall system's reliability. Their approach was to geographically divide the SC map to grids and to determine the number of stores in each grid.

Based on the longitude and latitude each store will resemble a point on the gridded map. This point (store) can be supplied by a maximum of one local distribution center, which is consequently supplied by a global DC. The reliability of fulfilling the order of one store (point on the map) before a certain due date decreases as its distance from the capable Local Distribution Center (LDC) increases, and vice versa. Building from down to top the reliabilities of each store is calculated, then for each block and finally the whole system. The reliability of a block of stores is calculated taking into account the store intensity (number of stores per block), their demands, individual reliabilities and possible supplying scenarios inside the block. Eventually the authors investigated the possibilities of dropping one GDC or more on the system's overall reliability. Hence, they rated the importance of each GDC for the entire SC. The results of the authors' work were logically sound as they have indicated that the GDCs close to the high intensity areas were much more important than the others serving low intensity grids. The authors' work was primarily descriptive and didn't offer a way to operate the SC taking into consideration, component capacities and modes. Their work showed how the overall reliability would be affected by various GDC failures and different scenarios, however on the operational level the SC will not be affected much. This research serves the SC in the case study as it pinpoints to it the highly important GDC.

You et al (2008), on the other hand, tackled the issue of operating a responsive SC under demand uncertainty. The authors defined responsiveness to be the ability of a supply chain to respond rapidly to the changes in demand, both in terms of volume and mix of products, and assumed that the demand distribution can follow either a normal or a triangular distribution. The lead time was thought of as the summation of the production lead time; that is the lead time from the supplier to the distribution center, and the delivery lead time from the distribution center to the final customers. Safety stock which is the primary hedge against uncertainty can be placed at the distribution centers and affects the lead time consequently via the probability of its stock out.

The mathematical model formulated was non-linear and had a bi-criterion objective function with both continuous and binary decision variables. Hence, the authors opted to formulate a heuristic to solve the problem in a practically convenient duration. You et al’s research shows that the distribution-to-customers link is a pivotal point in the determination of the overall SC responsiveness. Taking Goldratt et al’s (1986) definition of responsiveness which adds delivery reliability as the second component to lead time, then You et al's research is in congruence with Wang's where the reliability of the entire SC was determined from the distribution process entirely. However, this work lacks an important operational criterion that affects the lead time among components drastically, that is the transportation modes. Additionally, the manufacturer’s link was overlooked when the distribution phase was the only side studied in this research.

Considering the batch size, it was proven analytically that smaller batch sizes strongly advocated by the lean philosophy increases the reliability of delivery between the supplier and the buyer in a SC (Nieuwenhuyse and Vandaele 2006). The authors considered the variance of the delivery times of the first batch in a lot, to the buyer, to be indicative of the transportation reliability. Investigating the supplier-buyer relationship in a two tier SC, the authors considered the setup time, processing times and delivery times to be all stochastic and follow general independent and identical distributions with specific means and variances. It was found that the variance of the lot-for-lot policy always exceeded that of the lot split with a positive number. Hence, it was concluded that under the same conditions the lot split should result in higher delivery reliability. The authors then derived an approximate formula to calculate the delivery reliability and validated it using simulation. After finishing their study the authors reaffirmed the superiority of lot splitting in enhancing the delivery reliability claiming that it will provide more accurate production schedules for the buyer and consequently for the SC. A criticism for this work might be that it doesn't inform the readers with the optimum batch quantity to be transported. Additionally, operating batch sizes coupled with different transportation modes is not included in this research which only concerns itself with two tiers each one with one component only.

While Wang, Lu and Kvam (2006) considered reliability of SC as being a spatial function and Nieuwenhuyse and Vandaele (2006) tackled the SC reliability issue from the point of view of the predictability of delivery of the required batches, Quigley and Walls (2007) adopted a classic system's reliability approach for modeling and enhancing the reliability of SC. The authors analyzed a five tier aerospace SC and considered the reliability of the system to be the reliability of the final customer, or the top tier. When each component in the SC is allowed to undertake reliability improvement programs, at pre-specified costs, a certain reliability target can be met. The reliability target can be thought of as failure free operating times, or failure rates. Because each improvement activity cost a certain amount of monetary value hence elevating the component's reliability (and impacting the overall reliability) by different amounts the authors formulated a model based on game theory that provides a pareto-optimal solution for the synchronous choice of improvement activities in the whole SC. At the end of their work the authors showed that each coalition of components can be assigned a target level that can be met or exceeded by the individual components in that coalition and consequently achieving the overall system reliability. The authors showed that their approach based on Shapley's value (game theory) can be effective in trading the reliability targets fairly among the coalitions to produce the lowest cost of investment. The authors' work has a very limited scope that is to determine the improvement targets for various clusters of the SC based on an overall required reliability of the whole SC. Hence, this work, although handles the reliability component, has limited value in operational planning of SCs.

SC reliability is as well dependent on logistics and inventory management (Wlendahl, Cleminskl and Bagemann 2003). Like Nieuwenhuyse and Vandaele (2006), Wlendahl, Cleminskl and Bagemann (2003) in their analysis showed that lot splitting does impact the delivery reliability. However, the researchers didn't statistically prove that lot splitting results into lower transportation variability than lot-for-lot. The authors opted to investigate the issue of reliability from the point of view of SC inventory and its impact on logistics. Because inventory when regarded as a safety stock provides a certain service level (reliability of the component), and in the mean time it can have a powerful impact on the lead time when regarded as WIP. The authors offered a framework to be followed by SCM in order to optimize the operational performance while maintaining a certain level of service at each component. The framework the authors offered builds on logistic inventory operating curves developed by Lutz in 2001 as the authors attest. Those set of curves pinpoint the potential inventory reduction for achieving a certain service level and are plotted after taking into consideration the customer demand variations, due date deviations and under deliveries. In their criticism to the SCOR model the authors said that while it provides a huge set of operational metrics, the SCOR model is considered merely descriptive and not analytical in nature. The authors' framework was built on the notion that for a SC to be competitive it has to fulfill customer demands with high service levels and short lead times, while maintaining high utilization of resources and low inventory levels. In their paper the authors validated the results of their framework in a cutting tool manufacturing SC case study. Because the SC worked under high inventory policy, the WIP was huge and the lot sizes were unsynchronized which led to long lead times and lower than expected service levels even with the assistance of safety stocks at critical pivotal points. Upon ranking the inventory and following the framework proposed, the throughput time was reduced from 32.5 Shop Calendar Day (SCD) to 16.5 SCD and the final products inventory was decreased by 25%. The authors postulate that adopting the same framework in every component will yield significant advantages to the whole SC. After reading this article there was no clue given however about the charts that Lutz used and how to use them. The methodology section in this article lacks this very important piece of information and correspondingly it can be regarded as a direct application to Lutz's work.

Since forecasts lack certainty and it is an integral module of operations management; reliability of SC operations can be considered to be the reliability of the demand forecasts, or their degree of certainty (Ashayeri and Lemmes 2006). Ashayeri and Lemmes (2006) proposed a model that can measure the impact of various operational decisions made by the SCM on the demand reliability. The impact was measured in monetary values namely the Economic Value Added (EVA) compared to the degree of forecast enhancement, for the reliability of the demand forecast is a prime factor in determining the overall reliability of the SC. Considering a five tier SC, the authors studied the effects of changing the lead times, inventory levels and forecasting error on the demand reliability on a dynamic basis. The results were verified by investigating how the proposed model results reflected reality and it was validated by a case study of LG Philips.

Each component in the SC has certain reliability and its reliability depends on four factors: Supplier's reliability (SR), Country's Risk, Reliability of transportation (TR), and the supplier's suppliers reliability (RSS) (Levary 2008). In his study, Levary (2008) utilized the Analytical Hierarchy Process (AHP) to rank three foreign suppliers based on the above criteria. The four criteria, upon which Levary appraised the suppliers, were originally determined by the company's executives and consultants. Levary's SC reliability approach lacks the solid scientific ground that characterizes most of the scientific endeavor, using his words “the AHP the sole purpose of AHP is to provide relative ranking of the potential suppliers and it cannot handle correlation among criteria”.

In version six of the Supply Chain Operations Reference (SCOR) model, developed by the Supply Chain Council (SCC), reliability is considered to have three primary components: delivery performance, fill rate, and perfect order fulfillment which are primarily logistical factors. The SCOR model equates responsiveness though with one operational characteristic; that is order fulfillment lead time. Lead time is considered by others to be the main component of responsiveness in addition to delivery performance, which is one of the SCOR model reliability components (Goldratt and Fox 1986).

Adopting the Theory of Constraints developed by Goldratt (Goldratt and Fox 1986), William T. Walker urged that its application can include supply chains where the availability of the whole SC is determined by the availability of Capacity Constrained Resource (CCR) which is going to be the component with the lowest capacity (Walker 2005). Based on the lead time and consumption rates, the reliability can be calculated as the service level of the safety stock at the CCR. Like Goldratt’s theory, Walker’s work is not mathematically justified and can be classified under good operational policies.

2.3 Components Relationship and Cooperation

The relationship between the SC components, though intangible, has a sustantial impact on its responsiveness. A fact that is strongly adopted by the Japanese JIT philopshy (Lubben 1988). Nowadays it is hard to find an Operations Management textbook which doesn’t discuss the notion of “partnering” and its importance. In the literature some authors tried to analyze and quantify the relationship among SC components where their approach was primarly based on game theory for that purporse. Their analysis basically showed that cooperation among components maximizes both responsivenss of the SC and profit of the components in it.

Wang et al (2009) analytically studied the nature of outsourcing in SC. By claiming that lumpy demands will often necessitate outsourcing from a higher capacity component; outsourcing can be thought of as borrowing or lending this excess capacity to other components in the SC. The excess capacity will not be the same throughout the planning horizon and it will change continuously. Wang's study focused primarily on the production planning of two factories in the SC. Each factory is composed of manufacturing cells and has a predetermined demand that has to fulfill within the planning horizon. Hence each factory can either has a capacity exceeding demand or vice versa. In this study Wang proposed a mathematical model (MILP) to regulate both the production planning of each factory and the outsourcing process between them as well in a way that will maximize the net profit of the factories.

Because an MILP with lots of binary variables takes a considerable amount of time to be optimally solved, the authors formulated a heuristic based on Ant Colony Optimization (ACO) as it has the advantage of solving combinatorial NP hard problems in relatively short durations.

Considering a SC composed of two components a manufacturer and a retailer, Li et al (2009) proposed a mathematical model based on game theory that draws insight on the relationship between these two types of components in the SC. The authors considered two scenarios: the first one when the SC is centralized, i.e. when one component overwhelmingly dictates the relationship and the other scenario when the SC is decentralized. The first scenario is regarded to be a problem as it derives the whole SC into a passive and reactive mode. This finding was proven analytically using Nash bargaining model in this article as well. Additionally the authors found that in a SC when the decision making in decentralized both parties can make better profits. However, their study didn't shed light on other important qualitative factors like trust and partnering and their long term effect on competition. In this research it is assumed that components are cooperative and willing to work for the benefit of the SC as a whole, so in this sense SC manufacturers and dealers are decentralized with only the customers dictating the relationship. Centralized around customers and decentralized among them.

2.4 Safety Stock Utilization

A great deal of authors regards safety stocks as the best hedge against uncertainty. In fact this is the only significant reason that makes the lean philosophy risky. The optimum utilization of safety stocks makes the SC responsive as well as competitive. For that purpose it becomes important to include the utilization of safety stocks as an important factor in assessing responsiveness.

According to Jung et al (2008) Safety Stocks are the best hedge against uncertainties and is reflected in what is known as the service level. However, there are certain complexities when the issue is to manage the safety stock of a SC which includes the nonlinear behavior of the service level function for the whole SC and the interdependency among the components of the chain. The authors deduced the safety stock performance functions from discrete simulation and used them (after linearization) in an LP model. The model was then validated in the case study presented for the supply chain of a US polyethylene producer. The model formulated was to offer additional benefits than the base-stock policy that is generally adopted for its simplicity by SCM. However, the authors didn't include the effect of various transportation modes on the response time of the whole SC their view of responsiveness toke the transportation modes as given constants.

Simchi-Levi and Zhao (2005) formulated a Dynamic Programming (DP) Model to optimize the base-stock inventory replenishment policy that is widely used by companies. In their study the authors assumed that the SC takes exogenously, Poisson distributed orders which it has to respond to where the amount short is backordered and used a set of recursive equations in order to understand the nature of the backordering process. In their problem definition the authors assumed that the transportation and processing times are both stochastic. It was found that the sensitivity of stock positioning in the SC depends on the configuration of the SC itself whether it is sequential or divergent. However, the authors didn't mention how transporting items via different modes would impact the safety stock in the system.

Minner (2001) investigated the issue of safety stock management in reverse logistics supply chains. The researcher's point of view in this study is that the returning of products, and upon their disassembly, some of the items can be used as safety stock. Minner classified products to be external and internal and formulated a mathematical model that assists in managing safety stocks with the returned items incorporated. The researcher's premise is that inventory of items should increase by the anticipated items taken from returned products and management should act accordingly. The work adds insight about how to maximize the efficiency of the system by regarding its waste as resource. This has an impact on the way safety stocks should be managed but it doesn't offer an integrated module for safety stock management to maximize responsiveness.

In their article Yan et al. (2002) investigated the possibility of reducing the safety stock present in a SC while maintaining a certain service level. The backbone of their research builds on the classical safety stock equation that has the standard deviation of the demand and the lead time as its components. However, the authors' contribution was apparent in the proposal of different heuristics to solve the above mentioned problem and testing them. The authors regarded the demand at the top tier to be the most important one, and they assumed that in their SC the sequence of operations can be assumed of no importance. Without the technological constraint imposed on the SC which dictates certain precedence among tiers, the two primary components will be the lead time and added value cost for each operation.

The authors claimed that the BEST way to hedge against uncertainties in SC is to build inventory directly in the face of demand fluctuations. The authors offered a heuristic (GA) to find a solution of the sequencing of the operations in the SC which happens to be an NP-hard problem. The authors claim that their work offered insight on how the SC should be managed for example they found that operations with long operation times and lower value added costs should be moved from the upstream to the downstream.

In their work the Sourirajan et al (2007) considered one product (series system) and two products (where the series system branches at a point called the point of differentiation). They concluded that when the difference in lead times between the maximum and minimum operations (and value added cost) then the sequencing will not result into much decrease in the safety stock needed to hedge against uncertainties. The safety stock management principle here assumes that the adding value process can be shuffled i.e. there are no technical constraints which is not always the case.

2.5 The Literature Gap

Based on the above literature review it can be noticed that the articles dealing with SC responsiveness don't regard its operational nature in a holistic manner. That is the important factors in responsiveness are not included in one optimization model. This work attempts to integrate the relevant aspects in one mathematical model as all of the articles didn't take into consideration the effect of transportation modes on the SC responsiveness and mainly tackled the issue of responsiveness from the point of view of utilizing safety stocks in the distribution link. Hence, SC reliability was considered to be primarily that of distribution, suppliers or transportation and was not viewed from the perspective of being an integral part of responsiveness. Based on the literature survey, no single article optimized the SC operational planning based on a certain reliability criterion.

All of the mathematical models formulated were solved to determine the optimum batch sizes to be processed and transferred among SC components, however none of which included in addition to that the possibility of having various transportation durations, the effect of having safety stock, and/or where it is needed the most.

A great deal of the articles found were also descriptive in nature and reached logical conclusions at the end. However, these qualitative-in-nature articles, although may stress important attributes of responsiveness, don't provide much assistance for SCM to operate the SC with in terms of numeric analysis.

Points of Differentiation and Contribution

In the literature articles that deal with responsiveness can be categorized into:

- Articles that qualitatively study the issue of SC responsiveness
- Focus on a particular ingredient of responsiveness (transportation duration, batch sizes or safety stocks) only
- Study theoretical SCs (two components in two tiers, or maximum of four tiers)
- Formulate specific operational mathematical models for specific SCs (e.g. forest, or cutting tool)

The mathematical model formulated in this study, however, is generic, takes into account the three main ingredients of responsiveness, and can be used for any number of tiers or components. A tier in the SC network is indicated by precedence. Hence, pure suppliers are considered to be the first tier supplying a second tier of manufacturers which can feed another manufacturer, dealer or customer in the third tier, and so on till the last tier.

From the mathematical model, insights about responsiveness can be deduced. The effects of the interdependent ingredients are measured and assessed. To reach certain responsiveness level the three ingredients: batch size, transportation modes and safety stocks can be changed for that purpose, and if there exists a certain hurdle that prevents the reach of that level, the mathematical model pinpoints at the optimum location(s) which needs improvements. The elevation of SC performance based on the responsiveness level was not tackled before in the literature. Improvements can take the form of different transportation modes, increase of the level of safety stocks, or changing of the batch sizes. Most of the articles in the literature investigated the impact of one of these factors only on improving the responsiveness of the SC.

Chapter 3

Mathematical Model Development

After reviewing the literature and knowing the primary components of responsiveness the issue of optimizing the responsiveness of a SC was tackled as follows. First, a mathematical model was formulated that takes into account the important tangible characteristics found to be of great impact. Second, this model was built by OPL and solved by CPLEX two modules of the optimization software that builds and solves the mathematical model respectively. Third, the model was tested on SC cases and the output was then tested by changing the values of the input data and noticing the effect of these changes.

3.1 Mathematical Model

As with any modeling of reality systems certain assumptions were made during the abstraction process to facilitate the modeling without undermining the research contribution of this work. The assumptions made regarding SC were:

1. Production facilities and transportation modes are very reliable, i.e. no disturbances occur, hence we can assume that they are deterministic
2. The SC components are fixed, that is there are no other alternatives to the suppliers in the SC

3. One flow from upstream to downstream is allowed. That is there is no reverse direction or return of defective products (one of the literature review articles discusses this research point)
4. There are different transportation modes between the SC components which have different transportation durations and costs
5. Each transportation mode 'm' has a transportation duration equivalent to the numeric value of 'm'. In this model 'm' is 1, 2 or 3 equivalent to 1, 2 or 3 time periods. Practically, a fast transportation mode of 1 period could be a plane, two periods of a train and three periods a vehicle.
6. There is one type of product to be delivered to the final customer in the SC
7. The holding, production, shipping and outsourcing costs per unit item is constant

Table 1: Model Symbols Description

Symbol	Definition
Input Data	
Sets	
Ω_c	Set of Customers and its cardinality
Ω_d	Set of Dealers and its cardinality
Ω_I	Set of all components in the SC and its cardinality
Ω_m	Set of Pure Manufacturers and Assemblers and its cardinality
Ω_s	Set of Pure Suppliers (No Children) and its cardinality
Ω_{sm}	Set of Suppliers and Manufacturers and its cardinality
Input Parameters	
C_i	Production capacity of component i (Units/period)
CQ_i	The demand required by customer (retailer) i before due date DL_i (Units)
DL_i	The due date to deliver the demand required by customer i (Period number)
FC_{ij}	The fixed cost of transportation using mode 'm' to be used between (i) and (j) ($/shipment)
FD	Upper limit of the planning horizon (Period)
$FPcent$	The percentage of customer demand that can be outsourced (Decimal from 0 to 1)
IHC_i	Inventory holding cost of finished products of i and present at i ($/unit stored)

M	A large positive number
MC_i	Unit cost of producing material in component (i) ($/unit produced)
MPR_i	The minimum production run size for component (i) (unit)
$nModes$	Number of transportation modes
OC_i	Cost of 1 unit outsourced by dealer (i) ($/unit outsourced)
RHC_i	The cost of holding raw material at component (i) ($/unit stored)
$RMOC_{ij}$	Raw material outsourcing cost ($/unit outsourced)
TC_{ij}	Variable transportation cost between two components i and j for mode m ($/unit shipped)
WC_i	The warehouse capacity at component (i) (units)
X_{ij}	Binary factor indicating connectivity between i and j {0,1}
Decision Variables	
D_{ijtm}	Amount delivered from (i) to (j) in period (t) using mode (m) (units)
I_{it}	Inventory of products held at component (i) in period (t) (units)
O_{ijt}	Amount outsourced by (i) to substitute the deficit of (j) in period (t) (units)
OD_{it}	Amount outsourced by dealer (i) from outside the SC to satisfy part of the customer demands (units)
P_{it}	Products manufactured by (i) in period (t) (units)
RM_{ijt}	Raw material sent by (i) and held at (j) in period (t) (units)
S_{ijtm}	Amount to be shipped from (i) to (j) in period (t) using mode (m) (units)
Y_{ijtm}	Binary variable used if (i) ships to (j) in period (t) using mode (m) {0,1}
Z_{it}	Binary variable that is used to determine if production by component (i) takes place in period (t) (i.e. 1) or not (0) {0,1}

SC Operations Description:

Final customers order quantities from the SC to be fulfilled during specific periods. For the SC to be responsive it has to do so in the most economical way and with limited outsourcing. Components can ship to each others with one or more of three transportation modes. The transportation modes can transfer amounts in one, two or three periods at a fixed and variable costs which are unique for each link. All the SC components can hold finished goods inventory while manufacturers having other manufacturers as their children can hold also raw material inventory. Dealers and customers don't have production capacity.

Objective Function

$$Min \quad Z = Inventory\ Holdings\ Cost + Shipping\ Variable\ Cost + Shipping\ Fixed\ Cost + Production\ Cost + Raw\ Material\ Outsourcing\ Cost + Raw\ Material\ Holding\ Cost + Distributor\ Outsourcing\ Cost$$

$$Min \quad Z = \sum_{t}^{FD}\sum_{i}^{\Omega_I} I_{it} * IHC_i + \sum_{m}^{Modes}\sum_{t}^{FD}\sum_{j}^{\Omega_I}\sum_{i}^{\Omega_I} S_{ijtm} * TC_{ij} + \sum_{m}^{Modes}\sum_{t}^{FD}\sum_{j}^{\Omega_I}\sum_{i}^{\Omega_I} Y_{ijtm} * FC_{ij} + \sum_{t}^{FD}\sum_{i}^{\Omega_{sm}} P_{it} * MC_i + \sum_{t}^{FD}\sum_{j}^{\Omega_{sm}}\sum_{i}^{\Omega_{sm}} O_{ijt} * \mathrm{RMOC_{ij}} + \sum_{t}^{FD}\sum_{j}^{\Omega_{sm}}\sum_{i}^{\Omega_{sm}} RM_{ijt} * RHC_i + \sum_{t}^{FD}\sum_{i}^{\Omega_d} OD_{it} * OC_i$$

The objective function is a cost minimization function that minimizes the inventory holding costs and shipping costs (variable and fixed) via any available transportation mode of all the components, production, outsourcing (deficit), and raw material holding costs of the suppliers and manufacturers tiers, transportation variability and outsourcing from outside the SC.

Subject to:

Constraint (1): Finished goods inventory balance

$$Inventory = Inventory\ (previous\ period) + \ Production$$
$$- \ amounts\ shipped\ via\ all\ modes$$

$$I_{it} \ = \ I_{i(t-1)} + \ P_{it} - \ \sum_j \sum_m S_{ijtm} \qquad \forall\ t\ in\ Day, i\ in\ \Omega_{sm}\,, j\ in\ \Omega_I, m\ in\ Modes \quad (1)$$

Constraint (2): Shipping on valid links constraint

$$Shipped\ Amount\ \ \leq \{0, M\}$$

$$S_{ijtm} \ \ \leq \ X_{ij}\, M \qquad \forall\ t\ in\ Day, i\ in\ \Omega_I, j\ in\ \Omega_I, m\ in\ Modes \quad (2)$$

This relationship dictates that transportation should take place between certain tiers in the chain. Hence, not all the possible links are considered but only the ones which depict the actual SC configuration. The zero-one nature of the binary input parameter is used to make sure that not all the routes are open for transportation. The transportation modes (m) can further be refined using M in the transportation variable cost to act as penalty for certain impossible modes within the whole range of modes.

Constraint (3): Shipping-delivering constraint

$$Shipped\ Amount = Delivered\ Amount\ after\ a\ period\ 'm'$$

$$S_{ijtm} \ = D_{ij\,(t+m)m} \qquad \forall\ t\ in\ Day, i\ in\ \Omega_I, j\ in\ \Omega_I, m\ in\ Modes \quad (3)$$

Constraint (4): Shipping-binary constraint

$$Shipped\ Amount\ \leq Binary\ Variable * Big\ Number$$

$$S_{ijtm} \ \leq \ Y_{ijtm}\, M \qquad \forall\ t\ in\ Day, i\ in\ \Omega_I, j\ in\ \Omega_I, m\ in\ Modes \quad (4)$$

Shipping from (i) to (j) in period (t) via mode (m) should be recorded in the binary variable Y_{ijtm} . This binary variable is used in the objective function in the calculations of fixed costs of transportation or using a certain transportation mode per route. In other words, the consequences of choosing the mode of transportation and their frequencies are going to be incurred for in the objective function.

Constraint (5): Raw material inventory balance constraint

$$Raw\ material = Raw\ material\ (previous\ period) + \ amounts\ delivered\ by\ all\ modes$$
$$- amount\ produced + amount\ outsourced$$

$$RM_{ijt} \ = RM_{ij\,(t-1)} + \sum_m D_{ijtm} - P_{jt}$$
$$+ \ O_{ijt} \qquad \forall\ t\ in\ Day, i\ in\ \Omega_{sm}, j\ in\ \Omega_{sm}, m\ in\ Modes \quad (5)$$

Constraint (6): Production capacity constraint

$$amount\ produced\ \leq production\ capacity$$

$$P_{it}\ \leq\ C_i \qquad \forall\ t\ in\ Day, i\ in\ \Omega_I, j\ in\ \Omega_I \quad (6)$$

Constraint (7): Inventory balance for dealers

$$Inventory = Inventory\ (previous\ period) +\ amounts\ delivered\ by\ all\ modes$$
$$-\ amounts\ shipped\ by\ all\ modes + amount\ outsourced\ by\ dealer$$

$$I_{it}\ =\ I_{i(t-1)} + \sum_c \sum_m D_{citm}\ -\ \sum_p \sum_m S_{iptm}$$
$$+\ OD_{it} \qquad \forall\ t\ in\ Day, i\ in\ \Omega_d, c\ \ in\ \Omega_{sm+d}, p\ in\ \Omega_c, m\ in\ Modes \quad (7)$$

Constraint (8): Inventory balance for customers

$$Inventory = Inventory\ (previous\ period) +\ amounts\ delivered$$

$$I_{it}\ =\ I_{i(t-1)} + \sum_c \sum_m D_{citm} \qquad \forall\ t\ in\ Day, i\ in\ \Omega_c, c\ \ in\ \Omega_I, m\ in\ Modes \quad (8)$$

Constraint (9): Customers' needs constraint

$$Inventory\ at\ the\ customer\ by\ the\ due\ date \geq\ \ Customers\ demand$$

$$I_{i,DL_i}\ \geq CQ_i \qquad \forall\ i\ in\ \Omega_c \quad (9)$$

This constraint forces the model to fulfill customers demand at or before the required due date.

Constraint (10): Finished goods inventory initiation constraint

$$Inventory\ (first\ period) =\ 0$$

$$I_{i1} = 0\ \ \forall\ i\ in\ \Omega_I \quad (10)$$

Constraint (11): Raw material inventory initiation constraint

$$Raw\ material\ inventory\ (first\ period) = 0$$

$$RM_{ij\,1} = 0\ \ \forall\ i,j\ \ in\ \Omega_{sm} \quad (11)$$

Constraint (12): Supply chain outsourcing constraint

$$Total\ amounts\ outsourced\ \ \leq Failure\ percent * Total\ customes^{'}\ orders\ on\ SC$$

$$\sum_{i}^{\Omega_d} \sum_{t}^{FD} OD_{it}\ \ \leq FPcent * \sum_{i}^{\Omega_c} CQ_i \quad (12)$$

This constraint puts an upper limit on the dealer's outsourcing from outside the SC. Based on the presented example in this work, a 10% failure is allowed means that 90%, agreed on percentage, of the customers demand is fulfilled via the SC.

Constraint (13): Production- period constraint

$$Amount\ produced\ \ \leq Binary\ Variable * Big\ Number$$

$$P_{it}\ \leq\ Z_{it} M \qquad \forall\ i\ in\ \Omega_I, t\ in\ Day \quad (13)$$

This constraint is used to link between the production in one period with minimum production run (constraint 14).

Constraint (14): Minimum production runs constraint

$$Amount\ produced\ per\ period\ \geq minimum\ production\ run\ quantity$$

$$P_{it}\ \geq\ Z_{it} * MPR_i \qquad \forall\ i\ in\ \Omega_I, t\ in\ Day \quad (14)$$

Constraint (15): Storage capacity constraint

$$Inventory\ \leq Warehouse\ capacity$$

$$I_{it}\ \leq WC_i \qquad\qquad \forall\ i\ in\ \Omega_I, t\ in\ Day \quad (15)$$

Constraint (16): Production from raw material constraint

$$P_{jt}\ \leq RM_{cjt} \qquad c\ set\ of\ children\ of\ j \quad (16)$$

Constraint (17): Non-negativity constraint

$$D_{ijtm}\ , I_{it}\ , O_{ijt}\ , OD_{it}\ , P_{it}\ , RM_{ijt}\ , S_{ijtm} \quad \geq 0 \quad (17)$$

Constraint (18): Binary constraint

$$Y_{ijtm} \ , Z_{it} \ \in \{0,1\} \quad (18)$$

Minimax Model

The mathematical model formulated can be used to minimize the overall outsourcing per period. In this case the new objective function is:

$$Min \ \ Q \qquad (19)$$

All the constraints will not be changed however new constraints will be added:

$$O_{ijt} \ \ \leq Q \qquad (20)$$

$$OD_{it} \ \leq Q \qquad (21)$$

3.2 Model Characterization

The model developed is an MILP model, where both continuous and binary variables were used.

Using the cardinality of the above given sets the number non-negative real and binary variables as well as the constraints can be determined beforehand.

Table 2: Model Characterization

Decision Variable Type	Number	Count
Non-negative	$((2\Omega_I + \Omega_{sm}{}^2)Modes + \Omega_{sm}(\Omega_{sm} + 1 + \Omega_c) + \Omega_d * \Omega_c + \Omega_I)FD$	3060
Binary	$(\Omega_I{}^2 * Modes + \Omega_{sm})FD$	4428
Constraints	$(6\Omega_I{}^2 * FD * Modes) + (\Omega_{sm} * FD) + (3\Omega_{sm}{}^2 * FD) + (7\Omega_I * FD) + (2\Omega_d * FD) + (\Omega_c * FD) + \Omega_I + \Omega_c + \Omega_{sm}{}^2 + 1$	28552

The model formulated is solved in relatively short duration for short planning horizons; however for a longer planning horizon the execution duration will be increase as well. It is recommended to use computers with high computational capacity for solving extended duration planning horizons.

A tier in the SC network is indicated by precedence. Hence, pure suppliers are considered to be the first tier supplying a second tier of manufacturers which can feed another manufacturer, dealer or customer in the third tier, and so on till the last tier. The model formulated is flexible to accommodate multiple tiers based on requirement synchronizing production and shipping along all of them.

The mathematical model formulated differs from transshipment model in the sense that:

1. Transshipment model is primarily formulated for the distribution phase of a SC network, while this mathematical model includes production taking place upstream as well.
2. Assembly operations don’t take place in the transshipment model but it does in this one with one-to-one correspondence.

In this study the SC is triggered by customers’ demand, final tier, making the system act as pull system.

3.3 Solution Approach: CPLEX

CPLEX is a program developed by ILOG[2] to solve mainly linear optimization problems. It solves one type of nonlinear problems those which are quadratic. The variables can be continuous, integers or binary. Hence, this model can solve all the LP and MILP problems, but for nonlinear problems, NLP, the problem solver might need to resort to evolutionary heuristics or other programs.

CPLEX is very effective when dealing with large variables and constraints, because unlike other optimization software packages, it actually builds the model based on the programming instructions and then solve it. However, for large numbers of binary variables the program becomes slow and in some cases will not converge to a solution, which makes heuristics a good enough alternative for optimization.

[2] ILOG - OPL Studio User Manual

Chapter 4

Computational Results

4.1 Base Case

The model has been tested on a base case supply chain shown in Figure 3. The supply chain is composed of customers 1, 2, 3 and 4, Dealer 5, manufacturers 6, 8 and 9 and pure suppliers 7, 10 and 11. The supply chain data are tabulated in Figure 4. The data includes the production capacity per period of each component. Customers,-pure receivers- and dealers don't have production capacities. For each customer the required quantities and deadlines (in the form of period number) are tabulated. At each component inventory can be stored at a given holding cost per period. To differentiate between the final product of the component and the ingredients (raw materials to be processed) two types of inventories are presented at each component there are finished product (component's own production) and raw material (coming from the component's children).

In addition to the holding costs, the production cost per unit is also included where applicable. Each component can ship to its parent in one, two or three periods. The fixed and variable costs on each link are given in Tables 3 and 4.

After optimizing the SC the value of the objective function is the minimum cost of responsiveness to customers' demands.

Supply Chain Configuration:

Components	1	2	3	4	5	6	7	8	9	10	11
Production Capacity						45	48	40	44	24	23
Production Cost						600	400	500	500	240	200
Min Production Lot						5	5	4	5	3	3
RM Inv. Holding Cost						5		4	3		
FP Holding Cost	7	5	4	6	5	6	7	4	4	4	4
Quantity	30	30	30	30							
Due Dates	12	11	10	9							

Figure 3: Base Case Configuration Data

Table 3: Variable shipping cost via each mode

	Shipping Costs/Item		
Link	m=1	m=2	m=3
<5,1>	17.4	12.6	6.3
<5,2>	16.2	11.2	7.3
<5,3>	17.7	14.3	7.1
<6,4>	15.8	14.7	7.2
<6,5>	15.0	13.0	5.3
<7,6>	19.2	12.2	4.6
<8,6>	15.7	11.0	4.3
<9,6>	18.3	13.1	4.1
<10,8>	19.7	14.2	6.9
<10,9>	18.0	10.3	6.9
<11,8>	16.7	13.2	6.1
<11,9>	17.0	11.0	5.0

Table 4: Fixed transportation cost per mode

	Fixed Shipping Cost		
Link	m=1	m=2	m=3
<5,1>	109	55.0	53.0
<5,2>	114	94.0	50.0
<5,3>	119	95.0	55.0
<6,4>	112	61.0	54.0
<6,5>	147	61.0	48.0
<7,6>	134	95.0	80.0
<8,6>	107	63.0	78.0
<9,6>	145	91.0	46.0
<10,8>	113	77.0	44.0
<10,9>	120	83.0	62.0
<11,8>	107	56.0	44.0
<11,9>	150	80.0	66.0

In Tables 3 and 4, each transportation mode ‘m’ has a transportation duration equivalent to the numeric value of ‘m’. In this model ‘m’ is 1, 2 or 3 equivalent to 1, 2 or 3 time periods.

4.2 Results and Discussion

The base case was the primary case of investigation on which the insights were drawn from. The first scenario assumes that the SC isn’t overloaded beyond its capacity. In this case it was found that in 30 periods (and in 25 periods as well) the SC can fulfill all the customer requirements with no problem as no actual ‘work’ by the SC took place before the 14th period. The objective of this optimization scenario was to fulfill the SC customers’ demands 30 units each, total 120 units, by different due dates. The SC had 16 periods where no production or shipping took place hence they may be called slack periods. No outsourcing was needed whatsoever for any of the components or final products from outside of the SC, which means that the SC was actually capable to supply the entire load on it internally without the help of outsiders.

The mathematical model shows its first application here which is providing the optimum management of resources when responding to customers' demands. In that sense, solving the model revealed the un-necessity of working from day one hence the endeavor was postponed in order not to incur much inventory holding costs. The SC which can respond to customers' demands in a specified planning horizon with more slack periods should be considered more capable (time wise) than another SC working under the same load.

On the other hand when the base SC was further loaded by reducing the planning horizon time from 30 periods to 12 only, it became evident that this forms an overload on the SC itself which resulted into forcing the SC to outsource from outside. Tables 6, 7, 8 and 9 show the scenario for the SC working to fulfill customer demands in 12 periods.

The following can be noticed about this scenario.

- First the SC lacked a total of 28 units that the customer needed. Hence out of the 120 units required, 94 were supplied internally, 12 units (the agreed on fail percent of 10%) was outsourced by dealers from outside the SC. The raw materials to produce 16 units by component 6 were outsourced from outside as well.
- Second, outsourcing revealed an interesting aspect related to dependability as well. Components seven, eight and nine are the suppliers of component six. However, raw materials to compensate for shortages of components eight and nine were only needed. This shows that these two links (from 8 to 6) and (from 9 to 6) are vulnerable to failure when an overload on the SC takes place. In essence these two links are the weakest and the ones which need improvement to increase the responsiveness of the whole SC. But this is part of the explanation.

Components 8 and 9 are shown as the weakest links yet they don't have low capacity. The judgment on the links eight-to-six and nine-to-six as the weakest links might seem counterintuitive at the beginning because improvements are needed at components with higher capacities, but actually after looking at the configuration of the SC itself (Figure 4) it can be noticed that components 10 and 11 actually impact eight and nine as they are their sole suppliers.

Table 5: Base Case Components Production Capacity

Components	1	2	3	4	5	6	7	8	9	10	11
Production Capacity						45	48	40	44	24	23

Table 6: Production Schedule for the Base Case over 12 Periods

	Production, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
6				16			11.5	20.5	30	30		
7	16			11.5	20.5	30	30					
8				11.5	4.5	4	19	23	30			
9				11.5	20.5	20	5	5	30			
10	24	24	24	24	24	24	24	16				
11	23	23	23	23	23	23	23	23				

Table 7: Inventory Level in the Base Case over 12 Periods

	Inventory, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
1												30
2											30	30
3										30	30	30
4									30	30	30	30

Table 8: Outsourced Units in Base Case over 12 Periods

	Outsourced, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5							12					
6 (for 8)				16								
6 (for 9)				16								

Table 9: Shipping from-to Base Case

From/to	**Shipping, number of units**											
	Periods Quantity(to, mode)*											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5							28(3,3)	2(3,2)		30(2,1)	30(1,1)	
6				16(5,3)			2(5,1) 9.5(4,2)	20.5(4,1)	30(5,1)	30(5,1)		
7	16(6,3)			11.5(6,3)	20.5(6,3)	30(6,3)	30(6,3)					
8				11.5(6,3)	4.5(6,3)	4(6,3)	16(6,1) 3(6,2)	23(6,1)	30(6,1)			
9				11.5(6,3)	20.5(6,3)	20(6,3)	5(6,2)	5(6,1)	30(6,1)			
10	11.5(8,3) 12.5(9,3)	4.5(8,3) 19.5(9,3)	4(8,3) 20(9,3)	19(8,3) 5(9,3)	23(8,3) 1(9,3)	4(9,2) 20(8,3)	24(9,2)	10(8,1) 6(9,1)				
11	11.5(8,3) 11.5(9,3)	4.5(8,3) 18.5(9,3)	4(8,3) 2(9,2) 17(9,3)	3(9,2) 1(9,3) 19(8,3)	14(8,3) 4(9,2) 5(9,3)	7(8,3) 16(9,3)	9(8,1) 14(9,2)	23(8,1)				

***The entries in the table reflect the quantity shipped on a given link using a specific mode. For example in period 1, component 7 ships 16 units to component 6 using mode 3.**

The optimization model by deciding to outsource the raw materials needed from components eight and nine was actually finding a replacement for the whole sub-chains extending from the upstream components 10 and 11. It was more cost effective and less time consuming to outsource part of the load that needs to be done by 8 and 9 right away instead of purchasing raw materials that need to be worked on and processed by 8 and 9 themselves before being shipped to component six.

Although components 10 and 11 appear as underperformers what actually needs to be improved is the link connecting 8 and 9 with each one of them. No outsourcing was needed to compensate for component any shortages from 7 which mean that this branch is robust. The production capacities of 10 and 11 are the ones which need to be elevated; they are both bottlenecks to the whole supplying process.

The mathematical model takes advantage of the various transportation modes by utilizing them all at the same time. For example in period 7, component 8 produced 19 units and shipped 16 of them using one period transportation mode, and the other three will be delivered after two periods. The multi transportation modes not only offer flexibility but also they are more desirable economically.

It can be noticed that no inventory buildup was formed at any of the components, but the customers at the end. This is against the lean philosophy and uneconomical. However, the amount outsourced for each of the links (from 8 to 6) and (from 9 to 6) can be regarded as safety stock that if were there at this time the SC wouldn't need to outsource from outside. This is another advantage of revealing that outsourcing is needed at specific points, if the production capacity of the child can't be raised, or no faster transportation routes are present then the problem can be solved if certain level of safety stocks were present during this period at the parent. In this case an amount equal to 16 units from the products of component eight and nine are to be present at period four for the SC not to resort to outside outsourcing.

4.3 Model Verification

To make sure that the model is free of errors, verification was required. The mathematical model formulated was verified by changing the parameters and noticing the optimal solution change in correspondence. The parameters were changed so that in one case the inventory and raw material holding costs are reduced, encouraging the SC components to make and store. In another scenario the shipping costs (both fixed and variable) were reduced to entice the components to ship more. Changing the production capacity was examined by elevating the production capacity of the components in the SC. To validate this model, however, it was required to compare the model with real life case, which wasn't accomplished in this work for the lack of data.

4.3.1 Holding Cost Effect

When the parameters of the holding costs were reduced the SC became in favor of storage and this should be reflected, logically, in the utilization and keeping of inventory of both finished products and raw materials. This actually took place and is evident in the model's optimal solution as shown in the following tables.

Compared to the solution of the base case with original input data, the SC resorted to high inventory policy. In the production (table 10) the highlighted entities are production lots scheduled as in the original base case SC while all the other entities have changed. The production schedule in the SC favoring storage scenario has the following two characteristics:

1. It is sparse relative to the original.

Table 10: Production Schedule Base Case with Low Inventory Holding Costs

	Production, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
6				5	43			30		30		
7		48			30		30					
8			4	40			36	24				
9				20		36			24			
10	24	24	16	24	24	24	24	24				
11	23	23	23	23	23	23	23	23				

Table 11: Inventory Base Case with Low Holding Costs over 12 Periods

	Inventory, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
1												30
2											30	30
3										30	30	30
4									30	30	30	30
5							18					
6				5								
8							6					
10				24	12							
11			2	25	14	1						

Table 12: Outsourced Base Case with Low Holding Costs over 12 Periods

	Outsourced, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5								12				
6 (for 8)				1	3							
6 (for 9)				5	23							

Table 13: Shipping from-to Base Case with Low Holding Cost

From/to	**Shipping, number of units**											
	Periods Quantity(to, mode)											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5							30(3,3)	30(2,3)			30(1,1)	
6					48(5,2)			30(4,1)		30(5,1)		
7		5(6,1) 43(6,3)			30(6,3)		30(6,3)					
8			4(6,1)	40(6,1)			30(6,1)	30(6,2)				
9				20(6,1)		36(6,1)			24(6,1)			
10	24(8,1)	4(8,1) 20(9,2)	16(8,1)		36(8,1)	36(8,1)	24(8,1)	24(8,3)				
11	4(8,1) 19(8,3)	23(9,2)	21(8,1)		34(9,1)	36(8,1)	24(8,1)	23(9,1)				

2. Larger production lots per period (48 compared to a maximum of 30 in the original).

Both characteristics are indicative to the high inventory production environment, where the holding costs are considered abysmal. The number of shipments decreased as well in this scenario (33 compared to 61 in the base case).

The direct manifestation of this phenomenon is seen in the increase of the inventory of the supply chain. Apart from the customers 120 required units, there is a total of 107 units held in inventory in components 5, 6, 8, 10 and 11 which didn't store anything in the base case scenario.

The outsourcing policy was impacted as well. Dealer (component five) will still have to outsource 12 units, evident to be a deficit in the entire SC, whereas the outsourcing of raw materials changed as a result of changing the production schedule. This comparison is summarized in table 14 below. Reducing the holding cost resulted into decreasing the cost of responsiveness.

Table 14: Comparison Base Case and Reduced Cost

	Base Case (A)	**Reduced Holding Cost (B)**
Inventory Level	Customers Only	Increased at 5, 6, 8, 10 and 11
Production	30 units (max)	48 units (max)
Shipping	61 shipments	33 shipments
Outsourcing	12 (dealer) 32 (components 8 and 9)	12 (dealer) 32 (components 8 and 9)

4.3.2 Shipping Cost Effect

When the above SC's parameters were changed so that transportation costs are minimized while the holding costs increased; the SC operational planning changed accordingly towards favoring shipping more frequently. The following tables show the operational planning for the SC under these circumstances. After reducing the shipping fixed and variable costs the following can be noticed:

1. In the production planning schedule, no lot exceeded a maximum of 30 units which occurred only twice.

Table 15: Production Schedule Base Case with Low Shipping Costs

	Production, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
6					10	26		19	23	30		
7			10	26		19	23	30				
8		10	22	4		9	23	7	23			
9			14		19	23	14		16			
10	24	22	23	23	23	23	23	23				
11	23	23	23	23	23	23	23	23				

Table 16: Inventory Level Base Case with Low Shipping Cost

	Inventory, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
1												30
2											30	30
3										30	30	30
4									30	30	30	30

Table 17: Outsourced Base Case with Low Shipping Cost

	Outsourced, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5							5	7				
6 (for 8)								10				
6 (for 9)					10	12						

Table 18: Shipping from-to Base Case with Low Shipping Cost

From/to	**Shipping, number of units**											
	Periods Quantity(to, mode)											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5							30(3,3)	7(2,3)		23(2,1)	30(1,1)	
6					10(5,2)	11(4,3) 15(5,1)		19(4,1)	23(5,1)	30(5,1)		
7			10(6,2)	26(6,2)		19(6,2)	23(6,2)	30(6,2)				
8		10(6,3)	22(6,3)	4(6,2)		9(6,2)	23(6,2)	7(6,2)	23(6,1)			
9			14(6,3)		19(6,3)	23(6,3)	14(6,3)		16(6,1)			
10	10(8,1) 14(9,2)	22(8,1)	4(8,1) 19(9,2)	23(9,2)	9(8,1) 14(9,2)	23(8,1)	7(8,1) 16(9,2)	23(8,1)				
11	10(8,1) 13(8,2)	9(8,1) 14(9,1)	4(8,1) 19(9,2)	23(9,2)	9(8,1) 14(9,2)	23(8,1)	7(8,1) 16(9,2)	23(8,1)				

2. Apart from the final customers (1, 2, 3 and 4) no inventory buildup was encountered in any of the other components.
3. The number of shipments increased from 33 to 52.
4. The SC deficit of 12 units still exists

Reducing the fixed and variable costs enticed and increased the mobility in the SC causing fewer inventories to be accumulated and a significant increase in the number of transportations. The deficit of 12 units remains and should remain because this is the maximum capacity of the SC under current circumstances to respond to 108 of customer demands in this planning horizon internally. Table 19 summarizes the comparison between reduced cost and reduced shipping cost. The cost of responsiveness decreased compared to the base case as a result of reducing the shipping cost.

Table 19: Comparison Reduced Cost with Reduced Shipping

	Reduced Holding Cost (B)	**Reduced Shipping and Increased Holding (C)**
Inventory Level	Increased at 5, 6, 8, 10 and 11	Customers only
Production	48 units (max)	30 units (max)
Shipping	33 shipments	52 shipments
Outsourcing	12 (dealer) 32 (components 8 and 9)	12 (dealer) 32 (components 8 and 9)

4.3.3 Production Capacity Effect

High production capacities coupled with fast transportation modes should increase the SC responsiveness provided that they are properly synchronized. To further verify the model the production capacity of the whole components were raised. This should have an impact on the amount to be outsourced from outside the SC and on the overall capability of the SC. A more capable SC should respond to customer demands without much effort. In that sense slack times, where the whole SC is not actively working of customer demands by producing or shipping them, will increase. The following tables show the effect of elevating (doubling) the production capacity of the SC components.

As, logically, expected when the production capacity for the components doubled the supply chain became self sufficient and required no outsourcing from outsiders. This SC is in essence more capable that the lower production capacity SC. Table 20 summarizes the comparison between the base case with doubled production capacity and the base case as is. The cost of responsiveness decreased as a result of decreasing outsourcing.

Table 20: Comparison between Base Case and Doubled Capacity Base Case

	Base Case (A)	**Double Capacity (D)**
Inventory Level	Customers Only	Inventory at 9, 10 and 11
Production	30 units (max)	72 units (max)
Shipping	61 shipments	27 shipments
Outsourcing	12 (Dealer) 32 (components 8 and 9)	No outsourcing needed
Slack Periods	zero	1

Table 21: Production Schedule Base Case with High Production Capacity

	Production, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
6								72	48			
7					72	48						
8					18		54	48				
9				46	28	46						
10	48	48	48	48	48							
11	46	46	46	46	46	10						

Table 22: Inventory Level Base Case with High Production Capacity

	Inventory, number of units											
	Periods											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
1												30
2											30	30
3										30	30	30
4									30	30	30	30
9				46	2							
10			6									
11				2								

Table 23: Shipping from-to Base Case with High Production Capacity

From/to	Shipping, number of units											
	Periods Quantity(to, mode)											
Component	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
5									12(1,3) 30(3,1)	18(1,2) 30(2,1)		
6								30(4,1) 42(5,1)	48(5,1)			
7					72(6,3)	48(6,3)						
8					18(6,3)		54(6,1)	48(6,1)				
9					72(6,3)	48(6,3)						
10	48(9,3)	18(8,3) 30(9,3)	42(9,3)	54(8,3)	48(8,3)							
11	46(9,3)	18(8,3) 28(9,3)	46(9,3)	44(8,3)	48(8,3)	10(8,1)						

4.4 SC Responsiveness Graph

Compared to the 30-period scenario, the base case SC had to start production and shipping in the first period. This is logical because of the overload nature imposed on the SC in the 12 period scenarios. This resulted in no slack capacity ‘overall buffer’ present in the system. For analysis purposes it is proposed to estimate the responsiveness of a SC using this mathematical model and plotting a responsiveness curve. A responsiveness curve is three dimensional. One axis is the SC Output Rate (OR) which is total quantity/planning period. Another axis is the Slack Time (ST) present in the system, which is the time periods passed without production. The final axis is the Cost of Responsiveness (CR). The CR is the value of the objective function in the mathematical model.

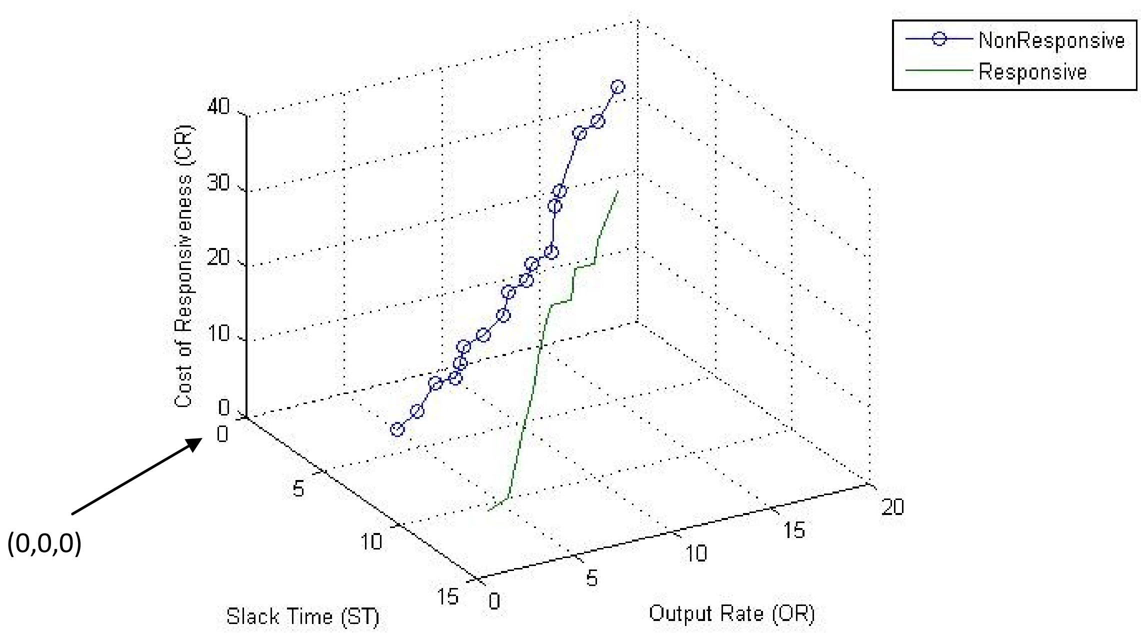

Figure 4: SC Responsiveness Curves

Figure 4 shows the dynamic relationship between the cost of responsiveness, slack time and the output rate required. The independent variable here is the output rate. When OR increases, it is expected that the CR will increase as well, and the slack time will decrease. Other SCs will have other graphs corresponding to the OR. The more responsive will have lower cost and slack time.

In the base case, both ST and OR are dependent on the planning horizon if everything else is fixed, however it is anticipated once the planning horizon is fixed and the customers demand increased the OR will increase as well causing the responsiveness curve to follow the same pattern.

From the SC responsiveness curve it can be shown that the more responsive SC will tend to have, for the same OR, lower cost associated with its responsiveness as well as larger slack times, although ultimately with high OR the SC will run out of slack time and the CR will skyrocket. Developing such curves for SCs will make them know how competitive they are relative to other SCs. After knowing their position in competition SCM can obtain accurate values of responsiveness cost, slack times based on the output rate required from the SC. SCM's aim will be to decrease the cost of responsiveness corresponding to the output rate by targeting improvements in shipping, production and/or outsourcing costs.

A responsiveness curve is drawn when the mathematical model is solved for different output rates. For example, in the case of 12 periods the output rate was ten (120/12) whereas for 30 periods the output rate becomes four. It is evident that as the output rate required from the SC increases the load on it will increase as well, resulting into choosing faster transportation modes which are usually more costly than slower ones. The SC can respond also with the same transportation modes and batch sizes on the expense of decreasing the slack time (which constitutes a safety factor). The cost of responsiveness is simply the value of the objective function from the mathematical model and it is very important for SCs to respond economically to survive the competition.

Chapter 5

Summary and Concluding Remarks

The operational factors affecting the Supply Chains (SC) responsiveness were researched. After reviewing the literature it was found that the primary factors include transportation durations, batch sizes and safety stocks. There are other factors as well like component relationships (e.g. partnering and supply chain order fulfilling configurations); however, the primary factors were used to formulate a mathematical model that upon its solution gives an optimum scheme for responding to customers demand.

The objective function of the mathematical model is a cost minimization function that has inventory holding, raw material holding, production, shipping and outsourcing costs associated with running the SC. Three modes of transportation are available for each SC component to ship with where each mode has its unique transportation duration.

Reducing the holding costs parameters in the model resulted in storing inventory producing and shipping in large lots. On the other hand, reducing the shipping costs resulted in shipping more frequently and in small lot sizes.

Elevating the production capacity impacted outsourcing from outside the SC, production and shipping. Larger lots were produced and shipped. Outsourcing was not needed and slack periods showing no production appeared.

Like elevating the production capacity, increasing the planning horizon resulted in increasing the slack periods, decreasing outsourcing and completely fulfilling customer demands. In both cases, elevating production capacity and increasing the planning horizon, the cost of responsiveness was minimum compared to the base case in which it was obligatory to resort to faster transportation modes and outsourcing to fulfill customer demands in the required periods.

Responsiveness graphs are plotted after knowing the cost of responsiveness, production slack periods corresponding to a certain output rate. Responsiveness graphs are drawn to compare among SCs. Responsiveness graphs are used to assess the cost of responsiveness of a SC with respect to its output rate.

Future Work

This work was concerned with the responsiveness of SCs with only one product. An extension to this work will be to include the effect of more than one product in the same chain. Each product might have a distinct BOM to add up to the complexity of the problem.

The problem formulated here assumed that all the parameters and variables are deterministic. This could be another direction to pursue in the future that is to assume that those parameters are stochastic in nature. Some of the factors that can follow a distribution are customer demands and transportation modes. Also a failure rate for the production facilities can add up to the complexity, as well as the reality, of the problem.

The next step will be to formulate a heuristic to solve the problem at hand when it becomes too large for CPLEX to converge to a solution.

Following a stimulus-response scheme, this research investigated how the SC system will function under one stimulus. In a dynamic environment the stimuli can occur sequentially on the planning horizon continuum giving rise to questions like how would the system respond when a customer asks for 30 units after 10 periods and other 20 after five periods from the first delivery? This is another point to be investigated in future research which is how the system will function when it is not totally capacity free from the start.

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